Robust magnetoplasmon spectrum of modulated graphene at finite temperature

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Abstract

In this work, we determine the effects of temperature on the magnetoplasmon spectrum of an electrically modulated graphene monolayer as well as the two-dimensional electron gas (2DEG). The intra-Landau-band magnetoplasmon spectrum within the Self Consistent Field (SCF) approach is investigated for both the aforementioned systems. Results obtained not only exhibit Shubnikov-de Hass (SdH) oscillations but also commensurability oscillations (Weiss oscillations). These oscillations are periodic as a function of inverse magnetic field. We find that both the magnetic oscillations, SdH and Weiss, have a greater amplitude and are more robust against temperature in graphene compared to conventional 2DEG. Furthermore, there is a π phase shift between the magnetoplasmon oscillations in the two systems which can be attributed to Dirac electrons in graphene acquiring a Berry's phase as they traverse a closed path in a magnetic field.

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I. INTRODUCTION

Remarkable progress made in epitaxial crystal growth techniques has led to the fabrication of novel semiconductor heterostructures. These modern microstructuring techniques have made possible the realization of two-dimensional electron gas (2DEG) system in semiconductor heterostructures. 2DEG is a condensed matter system where a number of novel phenomena have been observed over the years. One such phenomena was the observation of commensurability oscillations in physical properties when the 2DEG in the presence of a magnetic field is subjected to electric modulation. The electric modulation introduces an additional length scale in the system and the occurrence of these oscillations, commonly known as Weiss oscillations, is due to the commensurability of the electron cyclotron diameter at the Fermi energy and the period of the electric modulation. These oscillations were found to be periodic in the inverse magnetic field [1, 2, 3]. This type of electrical modulation of the 2D system can be carried out by depositing an array of parallel metallic strips on the surface or through two interfering laser beams [1, 2, 3].

One of the important electronic properties of a system are the collective excitations (plasmons). Weiss oscillations in the magnetoplasmon spectrum of 2DEG has been the subject of continued interest [4]. Recently, the fabrication of crytallites of graphene monolayer has generated a lot of interest. The study of this new material is not only of academic interest but there are serious efforts underway to investigate whether it can serve as the basic material for a carbon-based electronics that might replace silicon-based electronics. Graphene has a honeycomb lattice of carbon atoms. The quasiparticles in graphene have a band structure in which electron and hole bands touch at two points in the Brillouin zone. At these Dirac points the quasiparticles obey the massless Dirac equation. In other words, they behave as massless Dirac fermions leading to a linear dispersion relation $\epsilon_k = vk$ (with the characteristic velocity $v \simeq 10^6 m/s$). This difference in the nature of the quasiparticles in graphene from conventional 2DEG has given rise to a host of new and unusual phenomena such as anomalous quantum Hall effects and a π Berry's phase[5][6]. These transport experiments have shown results in agreement with the presence of Dirac fermions. The 2D Dirac-like spectrum was confirmed recently by cyclotron resonance measurements and also by angle resolved photoelectron spectroscopy (ARPES) measurements in monolayer graphene[7]. Recent theoretical work on graphene multilayers has also shown the existence

of Dirac electrons with a linear energy spectrum in monolayer graphene[8]. Plasmons in graphene were studied as early as in the eighties[9] and more recently [10]. In this work, we investigate magnetoplasmons in graphene monolayer when it is subjected to electric modulation at finite temperature. The zero temperature study was carried out by us in an earlier work [11] where we showed that the intra-Landau band magnetoplasmons exhibit Weiss oscillations and are present in the system due to the broadening of the Landau levels as a result of modulation. Presently, we extend our earlier work by taking into account the effects of temperature on the magnetoplasmons in graphene. While working on the finite temperature dispersion relation for magnetoplasmons in graphene we realized that finite temperature calculation for 2DEG is not available in the literature so in this work we also determine the finite temperature dispersion relation for magnetoplasmons in electrically modulated 2DEG. We find that the magnetoplasmons are more robust against temperature than those occurring in a conventional 2DEG realized in semiconductor heterostructures. Characteristic temperatures are determined for the damping of the magnetic oscillations (SdH and Weiss) in both the graphene and 2DEG systems. The experimental study of these should be as revealing as the enhanced magnetoconductivity prediction[12] and even more interesting: it bears directly on the many-body properties of the two-dimensional systems, as well as the frequency dependent transport and optical response.

II. ROBUST MAGNETOPLASMON SPECTRUM IN GRAPHENE AT FINITE TEMPERATURE

We consider two-dimensional Dirac electrons in graphene moving in the $x-y$-plane. The magnetic field (B_z) is applied along the z-direction perpendicular to the graphene plane. This system is subjected to weak electric modulation along the x-direction. We employ the Landau gauge and write the vector potential as $A = (0, Bx, 0)$. The two-dimensional Dirac like Hamiltonian for single electron in the Landau gauge is [1, 2, 8]

$$H_0 = v\sigma.(-i\hbar\nabla + eA). \tag{1}$$

Here $\sigma = \{\sigma_x, \sigma_y\}$ are the Pauli matrices and v characterizes the electron velocity. The complete Hamiltonian of our system is represented as

$$H = H_0 + V(x) \tag{2}$$

where H_0 is the unmodulated Hamiltonian and $V(x)$ is the one-dimensional periodic modulation potential along the x-direction modelled as

$$V(x) = V_0 \cos(Kx) \tag{3}$$

where $K = 2\pi/a, a$ is the period of modulation and V_0 is the constant modulation amplitude. Applying standard perturbation theory to determine the first order correction to the unmodulated energy eigenvalues in the presence of modulation we obtain

$$\varepsilon(n, x_0) = \hbar\omega_g\sqrt{n} + F_n \cos(Kx_0) \tag{4}$$

with $\omega_g = v\sqrt{\frac{2eB}{\hbar}}$ is the cyclotron frequency of Dirac electrons in graphene and n is an integer, $F_n = \frac{1}{2}V_0 e^{-\chi/2}[L_n(\chi) + L_{n-1}(\chi)]$ and $\chi = K^2l^2/2$, $x_0 = l^2k_y$, $L_n(\chi)$ are Laguerre polynomials and $l = \sqrt{\hbar/eB}$ is the magnetic length. The Landau level spectrum for Dirac electrons in graphene is significantly different from the spectrum for electrons in conventional 2DEG which is given as $\varepsilon(n) = \hbar\omega_c(n + 1/2)$, where ω_c is the cyclotron frequency.

The intra-Landau-band plasmon spectrum is determined within the Ehrenreich-Cohen self-consistent-field (SCF) approach[13]. The plasmon dispersion relation is given by

$$\tilde{\omega}^2 = \frac{16e^2}{k\bar{q}\pi}\frac{1}{al^2}\sin^2(\frac{\pi}{a}(x_0')) \times A_n, \tag{5}$$

$$A_n = \sum_n F_n \times \int_0^{a/2} dx_0 f(\varepsilon(n, x_0)) \cos(Kx_0) \tag{6}$$

where $x_0' = l^2q_y, \bar{q}$ is the two dimensional wave number, k is background dielectric constant and $f(\varepsilon(n, x_0))$ is the Fermi distribution function. This result was obtained previously in [11] where it was used to obtain the zero temperature dispersion relation. Here we are interested in temperature effects and we proceed as follows to determine the finite temperature dispersion relation. In the regime of weak modulation, the distribution function $f(\varepsilon(n, x_0))$ can be expressed as

$$f(\varepsilon(n, x_0)) \simeq f(\varepsilon_n) + F_n f'(\varepsilon_n) \cos(Kx_0), \tag{7}$$

where $f'(x) = \frac{d}{dx}f(x)$. Substituting the above expression for $f(\varepsilon(n, x_0))$, the integral over x_0 can be performed to yield the intra-Landau band plasmon dispersion relation at finite temperature as

$$\tilde{\omega}^2 = \frac{4e^2}{k\bar{q}\pi l^2}\sin^2[\frac{\pi}{a}(x_0')] \times B_n, \tag{8}$$

with $B_n = \sum F_n^2 \times [-f'(\varepsilon)]$. Related physics can be made more transparent by considering the asymptotic expression of intra-Landau band magnetoplasmon spectrum, where analytic results in terms of elementary functions can be obtained.

To obtain the asymptotic expression for the intra-Landau band plasmon spectrum we employ the following asymptotic expression for the Laguerre polynomials[12]

$$\exp^{-\chi/2} L_n(\chi) \rightarrow \frac{1}{\sqrt{\pi\sqrt{n\chi}}} \cos\left(2\sqrt{n\chi} - \frac{\pi}{4}\right) \tag{9}$$

Note that the asymptotic results are valid when many Landau Levels are filled. We now take the continuum limit:

$$n \,--> \frac{\varepsilon^2}{\hbar^2\omega_g^2}, \sum_{n=0}^{\infty} --> \int_0^{\infty} \frac{2\varepsilon d\varepsilon}{\hbar^2\omega_g^2}. \tag{10}$$

B_n that appears in the expression for $\tilde{\omega}^2$ in equation (8) can be expressed as

$$B_n = \frac{V_0^2}{\pi} \int_0^{\infty} \frac{2\varepsilon d\varepsilon}{\hbar^2\omega_g^2 \frac{\varepsilon}{\hbar\omega_g}\sqrt{\chi}} \frac{\beta g(\varepsilon)}{[g(\varepsilon)+1)]^2} \cos^2\left(2\sqrt{n\chi} - \frac{\pi}{4}\right) \cos^2\left(\frac{1}{2}\sqrt{\frac{\chi}{n}}\right) \tag{11}$$

where $g(\varepsilon) = \exp\beta(\varepsilon - \varepsilon_F)$, $\varepsilon_F = \hbar v K_F, K_F = \sqrt{2\pi n_D}$, n_D is the number density, $\chi = \frac{K^2 l^2}{2} = 2\pi^2/b$ with $b = \frac{eBa^2}{\hbar}$ and $\beta = \frac{1}{K_B T}$. Now assuming that the temperature is low such that $\beta^{-1} \ll \varepsilon_F$ and substituting $\varepsilon = \varepsilon_F + s\beta^{-1}$, we rewrite the above integral as

$$B_n = \frac{2V_0^2 \cos^2\left(\frac{\hbar\omega_g}{2\varepsilon_F}\sqrt{\chi}\right)}{\pi\hbar\omega_g\sqrt{\chi}} \int_0^{\infty} ds \frac{e^s}{[e^s+1)]^2} \cos^2\left(\frac{2\varepsilon_F\sqrt{\chi}}{\hbar\omega_g} - \frac{\pi}{4} + \frac{2\sqrt{\chi}\beta^{-1}}{\hbar\omega_g} s\right) \tag{12}$$

with the result

$$B_n = \frac{V_0^2 \cos^2\left(\frac{\hbar\omega_g}{2\varepsilon_F}\sqrt{\chi}\right)}{2\pi\hbar\omega_g\sqrt{\chi}} \left[2 - 2A\left(\frac{T}{T_W}\right) + 4A\left(\frac{T}{T_W}\right)\cos^2\left(\frac{2\varepsilon_F\sqrt{\chi}}{\hbar\omega_g} - \frac{\pi}{4}\right)\right] \tag{13}$$

where $A(\frac{T}{T_W}) = \frac{\frac{T}{T_W}}{\sinh(\frac{T}{T_W})} \; -^{(\frac{T}{T_W}-->\infty)} - >= 2\frac{T}{T_W}e^{-\frac{T}{T_W}}$, $\frac{T}{T_W} = \frac{4\pi\sqrt{\chi}K_B T}{\hbar\omega_g}$ and $T_W = \frac{\hbar\omega_g}{4\pi K_B\sqrt{\chi}}$ is the characteristic damping temperature of the Weiss oscillations. Substituting the expression for B_n in equation (8), the asymptotic expression for intra-Landau spectrum is obtained

$$\begin{aligned}\tilde{\omega}^2 &= \frac{2e^2}{k\bar{q}\pi l^2} \frac{V_0^2\cos^2\left(\frac{\omega_g}{2\varepsilon_F}\sqrt{\chi}\right)}{\pi\hbar\omega_g\sqrt{\chi}} \sin^2\left(\frac{\pi}{a}(x_0')\right) \\ &\quad \times \left[2 - 2A\left(\frac{T}{T_W}\right) + 4A\left(\frac{T}{T_W}\right)\cos^2\left(\frac{2\varepsilon_F\sqrt{\chi}}{\hbar\omega_g} - \frac{\pi}{4}\right)\right]\end{aligned} \tag{14}$$

The above expression is valid at high temperature ($K_BT >> \hbar\omega_g/2\pi^2$) and is not able to account for the SdH oscillations occurring in the magnetoplasmon spectrum. To take these into account we use the following expression for the density of states at low magnetic fields in the absence of impurity scattering given by $D(\varepsilon) = \frac{\varepsilon}{\pi l^2 \hbar^2 \omega_g^2}\left[1 - 2\cos\left(\frac{2\pi\varepsilon^2}{\hbar^2\omega_g^2}\right)\right]$. This expression for $D(\varepsilon)$ was obtained in [14] in the absence of scattering and gap $\Delta = 0$. The sum appearing in equation (6) can now be expressed in the continuum approximation as $\sum\limits_{n=0}^{\infty} -- > 2\pi l^2 \int\limits_0^{\infty} D(\varepsilon)d\varepsilon$. Therefore, the intra-Landau band magnetoplasmon dispersion relation that takes into account both Weiss and SdH oscillations is given by

$$\tilde{\omega}^2 = \frac{2e^2}{k\bar{q}\pi l^2}\frac{V_0^2\cos^2\left(\frac{\hbar\omega_g}{2\varepsilon_F}\sqrt{\chi}\right)}{\pi\hbar\omega_g\sqrt{\chi}}\sin^2\left(\frac{\pi}{a}(x_0')\right) \times \left\{\left[2 - 2A\left(\frac{T}{T_W}\right) + 4A\left(\frac{T}{T_W}\right)\cos^2\left(\frac{2\varepsilon_F\sqrt{\chi}}{\hbar\omega_g} - \frac{\pi}{4}\right)\right] - 4\frac{2X_{SdH}}{\sinh(X_{SdH})}\cos\left(\frac{2\pi\varepsilon_F^2}{\hbar^2\omega_g^2}\right)\cos^2\left(\frac{2\varepsilon_F\sqrt{\chi}}{\hbar\omega_g} - \frac{\pi}{4}\right)\right\} \tag{15}$$

where $X_{SdH} = \frac{4\pi^2\varepsilon_F}{\hbar^2\omega_g^2\beta}$, $\frac{T}{T_{SdH}} = \frac{4\pi^2\epsilon_F K_B T}{\hbar^2\omega_g^2}$ and $T_{SdH} = \frac{\hbar^2\omega_g^2}{4\pi^2\epsilon_F K_B}$ is the characteristic damping temperature of the SdH oscillations.

Following the same approach as given above for graphene monolayer, we can obtain the intra-Landau band magnetoplasmon spectrum for conventional 2DEG at finite temperature with the result

$$\tilde{\omega}^2 = \frac{4e^2 m^*\omega_c}{\hbar k\bar{q}\pi}\sin^2[\frac{\pi}{a}(x_0')] \times B_n(C), \tag{16}$$

where m^* is the standard electron mass, $B_n(C) = \sum F_n^2(C) \times [-f'(\varepsilon)]$, and $F_n(C) = V_0 e^{-\chi/2}L_n(\chi)$ is the modulation width of the conventional 2DEG. The corresponding asymptotic result is

$$\tilde{\omega}^2 = \frac{4V_0^2 e^2 m^*\omega_c}{k\bar{q}2\pi^2\hbar\sqrt{\chi\hbar\omega_c\varepsilon_F}}\sin^2\left(\frac{\pi}{a}(x_0')\right) \times \left\{\left[1 - A\left(\frac{T}{T_W^p}\right) + 2A\left(\frac{T}{T_W^p}\right)\cos^2\left(2\sqrt{\frac{\chi\varepsilon_F}{\hbar\omega_c}} - \frac{\pi}{4}\right)\right] - 4\frac{2X_{SdH}^p}{\sinh(X_{SdH}^p)}\cos\left(\frac{2\pi\varepsilon_F}{\hbar\omega_c}\right)\cos^2\left[2\sqrt{\frac{\chi\varepsilon_F}{\hbar\omega_c}} - \frac{\pi}{4}\right]\right\} \tag{17}$$

where $\frac{T}{T_W^p} = \frac{4\pi^2 k_B T}{\hbar\omega_c a K_F}$, $X_{SdH}^p = \frac{2\pi^2}{\hbar\omega_c\beta}$, $\frac{T}{T_{SdH}^p} = \frac{2\pi^2 k_B T}{\hbar\omega_c}$, $\chi = \frac{K^2 l^2}{2} = 2\pi^2/b$ with $b = \frac{eBa^2}{\hbar}$.

Now we can compare the exact results, for the temperature dependent magnetoplasmon in terms of the elementary functions, with those for a conventional 2DEG. The differences are:

- the standard electron energy eigenvalues scale linearly with the magnetic field whereas those for Dirac electrons in graphene scale as the square root.

- the temperature dependence of the Weiss oscillations, $A\left(\frac{T}{T_W}\right)$, is clearly different from that of the standard 2DEG, $A\left(\frac{T}{T_W^p}\right)$[3].

- the temperature dependence of SdH oscillations in graphene, $\frac{X_{SdH}}{\sinh(X_{SdH})}$, is different from that of the standard 2DEG, $\frac{X_{SdH}^p}{\sinh(X_{SdH}^p)}$[15, 16].

- the density of states term that contains the cosine function responsible for the SdH oscillations has a different dependence in each of the systems: $\cos\left(\frac{2\pi\varepsilon_F^2}{\hbar^2\omega_g^2}\right)$[14] and $\cos\left(\frac{2\pi\varepsilon_F}{\hbar\omega_c}\right)$ [15, 16] respectively.

These differences will give different results for the temperature dependent magnetoplasmon spectrum, as we discuss in the next section.

III. DISCUSSION OF RESULTS

The finite temperature intra-Landau band magnetoplasmon dispersion relation for electrically modulated graphene and 2DEG given by equations (15) and (17) are the central results of this work. These results allow us to clearly see the effects of temperature on Weiss and SdH oscillations in the magnetoplasmon spectrum of the two systems. We find that these two types of oscillations have different characteristic damping temperatures. This is easily understood if we realize that the origin of these oscillations is different. The SdH oscillations arise due to the discreteness of the Landau levels and their observation requires that the thermal energy K_BT acquired by the electrons at temperature T has to be smaller than the separation between the levels. Weiss oscillations are related to the commensurability of two lengths: the size of the cyclotron orbit and the period of the modulation, these oscillations will be observed if the spread in the cyclotron diameter is smaller than the modulation period. To elucidate the effects of temperature we present the magnetoplasmon spectrum in graphene and 2DEG at two different temperatures in Figs.(1) and (2).

In Fig.(1), we show the magnetoplasmon energy as a function of the inverse magnetic field in graphene monolayer at two different temperatures: $T = 1K$ and $12K$. The following parameters were employed for graphene[10, 11]: $k = 3$, $n_D = 3.16 \times 10^{16}$ m^{-2}, $v = 10^6 m/s$,

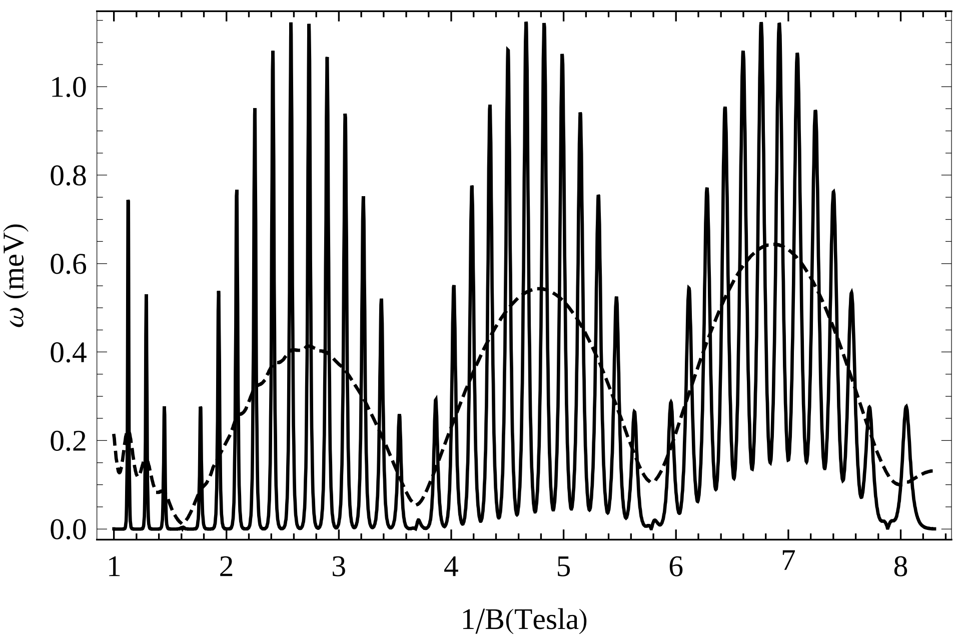

FIG. 1: Intra-Landau-band plasma frequency as a function of inverse magnetic field in a graphene monolayer at $T = 1\,\mathrm{K}$ (solid line) and $T = 12\,\mathrm{K}$ (dashed line).

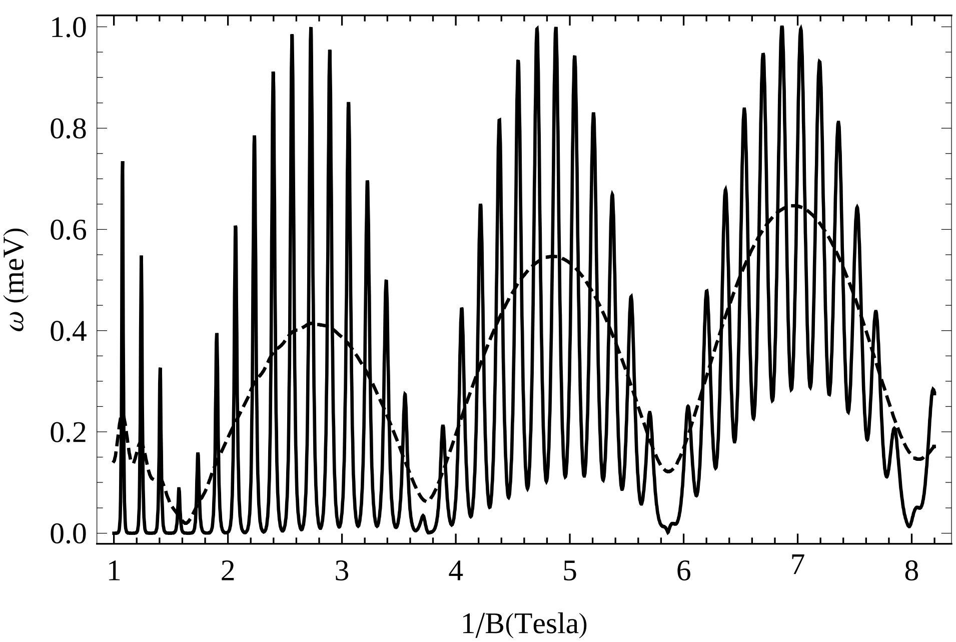

FIG. 2: Intra-Landau-band plasma frequency as a function of inverse magnetic field in a conventional 2DEG at $T = 0.3\,\mathrm{K}$ (solid line) and $T = 3\,\mathrm{K}$ (dashed line).

$a = 380$ nm and $V_0 = 1.0$ meV. We also take $q_x = 0$ and $q_y = .01k_F$, with $k_F = (2\pi n_D)^{1/2}$. Weiss oscillations superimposed on the SdH oscillations can be clearly seen in both the curves. In Eq.(15), the terms containing the characteristic temperature for Weiss oscillations T_w are mainly responsible for Weiss oscillations whereas terms containing T_{SdH} are responsible for the SdH oscillations. The intra-Landau-band plasmons have frequencies comparable to the bandwidth and they occur as a result of broadening of the Landau levels due to the modulation in our system. These type of intra-Landau-band plasmons accompanied by regular oscillatory behavior (in $1/B$) of the SdH type was first predicted in [17] for tunneling planar superlattice where the overlap of electron wavefunction in adjacent quantum wells provides the mechanism for broadening of Landau levels. The SdH oscillations occur as a result of emptying out of electrons from successive Landau levels when they pass through the Fermi level as the magnetic field is increased. The amplitude of these oscillations is a monotonic function of the magnetic field when the Landau bandwidth is independent of the band index n. In the density modulated case, the Landau bandwidths oscillate as a function of the band index n, with the result that in the plasmon spectrum of the intra-Landau band type, there is a new kind of oscillation called Weiss oscillation which is also periodic in $1/B$ but with a different period and amplitude from the SdH type oscillation. At $T = 12K$, we find that the SdH oscillations are washed out while the Weiss oscillations persist. From Eq.(15), we see that T_W and T_{SdH} set the temperature scale at which these oscillations will be damped. For the 2DEG, the magnetoplasmon energy as a function of inverse magnetic field is presented in Fig.(2) at two different temperatures: $T = 0.3K$ and $3K$. For conventional 2DEG (a 2DEG at the GaAs-AlGaAs heterojunction) we use the following parameters[1, 2, 3, 4]: $m^* = .07m_e(m_e$ is the electron mass), $k = 12$ and $n_D = 3.16 \times 10^{15}$ m^{-2} with the modulation strength and period same as in the graphene system. We find that the SdH oscillations in the magnetoplasmon spectrum die out at $T = 3K$ here while they are present at a higher temperature ($12K$) in graphene.

To compare the results for the two systems we show in Fig.(3) the magnetoplasmon spectrum as a function of the inverse magnetic field ($\frac{B'}{B} = \frac{\hbar}{Bea^2}$, where $B' = \frac{\hbar}{ea^2} = 0.0046$ Tesla) for both graphene (solid line at temperature $5K$) and 2DEG (dotted and dashed line at temperature $1K$ and $5K$ respectively). The oscillations in the conventional 2DEG have been damped out strongly at $5K$ but are well resolved, significant and have larger amplitude in graphene at the same temperature. This confirms that the graphene oscillations are more

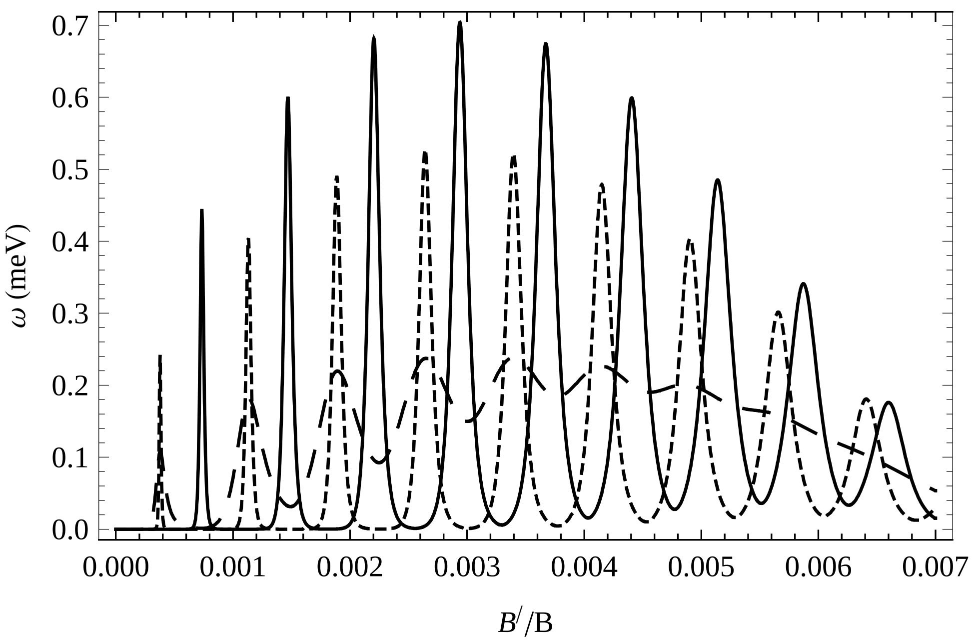

FIG. 3: Intra-Landau-band plasma frequency as a function of inverse magnetic field in the region of very strong magnetic field: solid line at $T = 5\,\mathrm{K}$ in a graphene monolayer; dashed ($T = 5\,\mathrm{K}$) and dotted ($1\,\mathrm{K}$) in standard 2DEG. $\frac{B'}{B} = \frac{\hbar}{eBa^2}$ where B is the magnetic field and $B' = \frac{\hbar}{ea^2} = 0.0046\,\mathrm{Tesla}$.

robust and enhanced against temperature than those in the conventional 2DEG. The magnetic oscillations, SdH and Weiss, have a higher amplitude in graphene compared to 2DEG. This can be attributed to the larger characteristic velocity ($v \sim 10^6 m/s$) of electrons in graphene compared to the Fermi velocity of standard electrons and smaller background dielectric constant k in graphene in contrast to conventional 2DEG. The temperature at which we expect the Weiss oscillations to dampen is determined by comparing the characteristic temperatures for Weiss oscillations in the two systems: $\frac{T_W^p}{T_W} = \frac{v_F}{v}$, the ratio of the characteristic temperatures is equal to the corresponding velocities at the Fermi surface[12]. For the parameters used in this work $\frac{T_W^p}{T_W} \sim 0.24$, implying that Weiss oscillations are damped at a higher temperature in graphene compared to the 2DEG. Similarly, damping of SdH oscillations can also be compared in the two systems through their corresponding characteristic temperatures: $\frac{T_{SdH}^p}{T_{SdH}} = \frac{\hbar K_F}{vm^*} \sim 0.23$ for $n_D = 3.16 \times 10^{15}\ \mathrm{m}^{-2}$ whereas it is ~ 0.74 for $n_D = 3.16 \times 10^{16}\ \mathrm{m}^{-2}$. Therefore, SdH oscillations are damped at a higher temperature

in graphene compared to 2DEG. Furthermore, our results also show that these oscillations in the magnetoplasmon spectrum differ in phase by π in the two systems which is due to quasiparticles in graphene acquiring a Berry's phase of π as they move in the magnetic field[6].

IV. CONCLUSIONS

We have determined the finite temperature intra-Landau band magnetoplasmon frequency for electrically modulated graphene as well as the 2DEG in the presence of a magnetic field employing the SCF approach. We find that the magnetic oscillations (SdH and Weiss) in the magnetoplasmon spectrum in graphene monolayer have a higher amplitude compared to the conventional 2DEG realized in semiconductor heterostructures. Moreover, these oscillations persist at a higher temperature in graphene compared to the 2DEG. Hence they are more robust against temperature in graphene. Furthermore, π Berry's phase acquired by the Dirac electrons leads to π phase shift in the magnetoplasmon spectrum in graphene monolayer compared to 2DEG.

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